NASA TECHNICAL MEMORANDUM

EXPLORING IN AEROSPACE ROCKETRY

1. AEROSPACE ENVIRONMENT

by John C. Evvard
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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John C. Evvard*

In the broad sense, the word "space" is all-inclusive. It includes the Sun, the Earth, and the other planets of the solar system. It includes the one hundred billion stars or more in our own galaxy, which we label the "Milky Way." It includes all the other galaxies of the universe which we see as nebulae. The great nebula in Andromeda is shown in figure 1-1. Certainly there are billions of stars in this disk-shaped conglomeration, some of which may have planets and living, intelligent beings. If the environment near these billions of stars is right for living forms, then life might exist on some of them, but this is a challenge for the future. Our solar system probably is not unique even in our own galaxy, and we know that there are billions of galaxies in the universe.
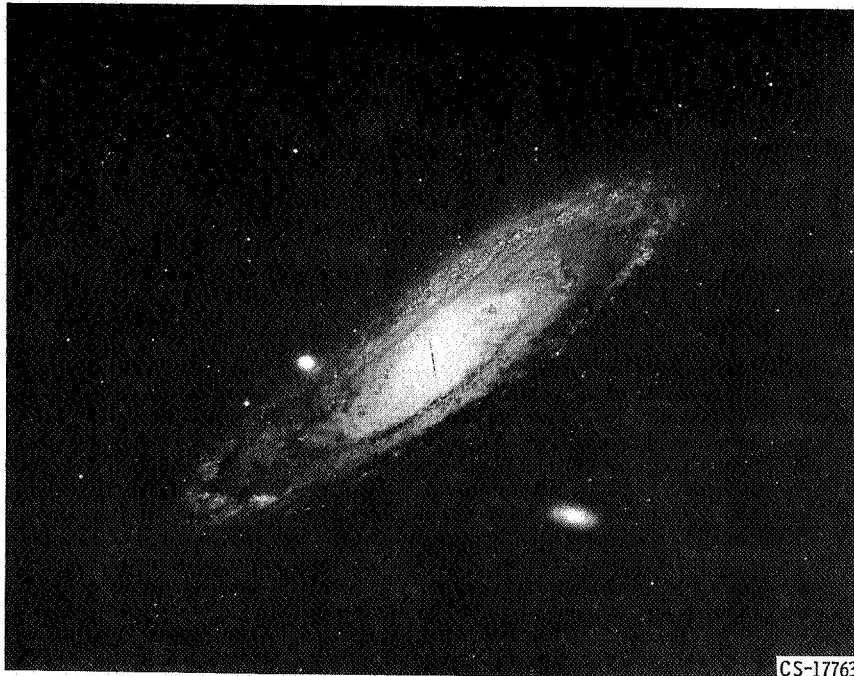

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Figure 1-1. - Great nebula in Andromeda.

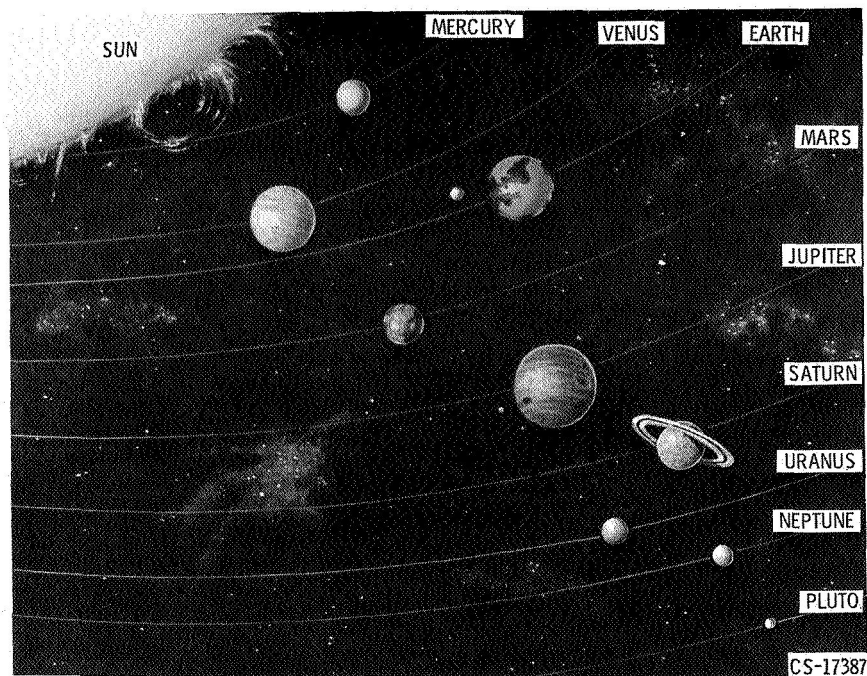---

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Figure 1-2. - Planets of the solar system.

The space environment includes all matter or the related lack of matter in the high-vacuum regions between the planetary and stellar mass concentrations. It likewise includes all excursions of matter through these regions and the influence that these meteoroidal excursions might have on a space ship contained therein. It includes all radiation, such as light, radiowaves, X-rays, and electromagnetic radiation. It includes all force fields, such as gravity, electrostatic attractions, and magnetic fields. Space environment must also include the probabilities of cosmic rays, solar winds, and lethal radiations associated with solar flares.

Solar space (fig. 1-2) is our primary concern. The Sun, which has a diameter of approximately 864 000 miles is the most important star to mankind. It is the principal source of energy in our solar system. While the internal temperature of this gigantic thermonuclear reactor is approximately 25 000 000° F, the temperature of the photosphere (the luminous surface visible to the unaided eye) is only about 10 000° F.

The Sun (fig. 1-3), however, is far from being a quiet, well-behaved source of heat and light. Intense storms project giant tongues of material into space (beyond the solar corona) at temperatures of millions of degrees. There are magnetic storms associated with sunspots that vary according to cycles of approximately 11 years. The Sun rotates on its axis and carries these sunspots across its surface in a 27-day period. Each of these periods influences the environment, weather, and atmospheres of the planets. In addition, the solar prominences project streams of charged particles and
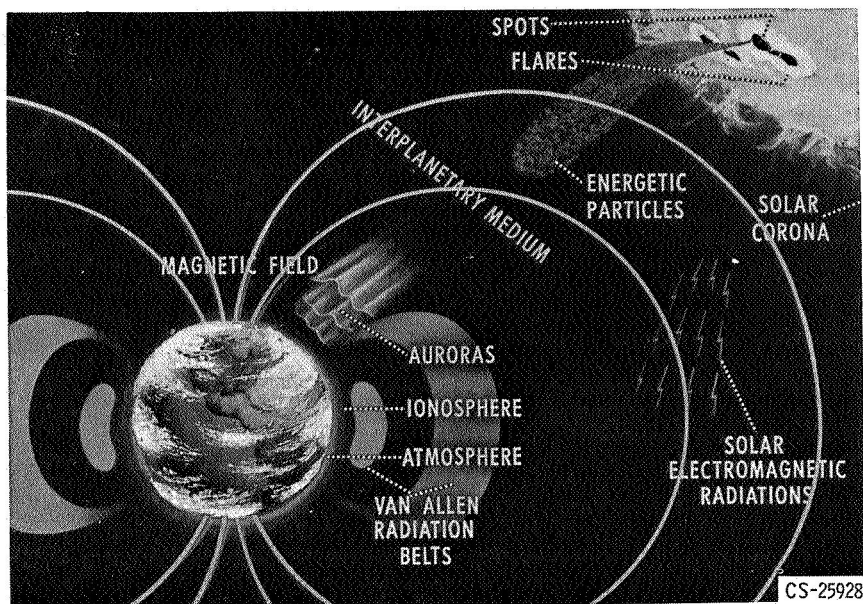
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Figure 1-3. - Solar system environment.

magnetism outward to bathe the planets in a varying solar atmosphere. This solar
atmosphere monotonically decreases in intensity as we proceed outward from the Sun's
surface past the planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus,
Neptune, and Pluto. The Earth's magnetic field traps some of these charged particles
to generate the Van Allen belts.

The intensity of radiation such as light and heat varies inversely as the square of
the distance from the Sun. At the Earth's distance of 93 000 000 miles from the Sun
(1 astronomical unit), the solar energy is 1.34 kilowatts per square meter. If this
value were to increase by only 10 percent, the Earth's weather would be drastically
altered, with the result that the polar ice caps would melt. A 5-percent decrease in
the orbital diameter of the Earth would cause this effect. An increase in the Earth's
orbital diameter would produce opposite and equally drastic results.

The known planets in the solar system have distances from the Sun ranging from
0.387 astronomical unit for the planet Mercury to 39.52 astronomical units for the
planet Pluto. Therefore, the radiant energy intensity received by a spacecraft moving
across the realms of solar space would vary by a factor of 10 000 in making a trip from
Mercury to Pluto. The planet Pluto is so far removed even from Earth (more than 300
light-minutes) that the probability of manned flight beyond the solar system is question-
able indeed. The nearest star is about 4.3 light-years away. (A light-year is the
distance that light, with a velocity of approximately 186 000 miles per second, will
travel in 1 year.)

It was mentioned previously that the space environment includes all of the force fields contained therein. One of these force fields, the gravitational attraction, holds very special significance. The force of gravity between two masses varies as the inverse square of the distance between them, and this relation is shown by the equation

$$f = G \frac{m_1 m_2}{r^2} \tag{1}$$

where f is the force of gravity, G is the gravitational constant, m_1 and m_2 are the two masses, and r is the distance between them. Because of this force, the planets are held in orbits around the Sun. For the general case, a planet will travel in an elliptical orbit around the Sun. The radius vector of a particular planet sweeps out equal areas in equal times. The square of the orbital period of a planet is proportional to the cube of the distance of that planet from the Sun. Crudely speaking, a planet remains in orbit because the centrifugal force associated with the speed of the planet and the curvature of the path just balances the gravitational attraction. If the planet were not moving, it would quickly fall into the parent body to become part of it.

The gravitational attraction of the Sun and planets also serves as a gigantic pump to remove most of the nonorbiting material from space; thus, it builds up life-sustaining atmospheres on the planets and leaves very high vacuum conditions in the regions between the planets. We must recognize, however, that this gravitational pump is not perfect, so that even the high vacuum regions may be regarded as the outer fringes of the solar and planetary atmospheres.

At the surface of the Earth, or sea level, our atmosphere exerts a pressure of 14.7 pounds per square inch (1 atmosphere); this pressure represents the weight of the atmosphere on each square inch of surface area. Atmospheric pressure decreases approximately by a factor of 2 for each 16 000-foot increase in altitude. This means that at each successive 16 000-foot step in altitude (starting from sea level) the pressure is one half the value of the preceding step, or level. Therefore, according to this general rule, the pressure is 1 atmosphere at sea level, 1/2 atmosphere at approximately 16 000 feet, 1/4 atmosphere at approximately 32 000 feet, etc. However, this rule provides only rough approximations of the actual values, shown in the following table:

Pressure, atm	Altitude, ft
1/2	18 000
1/4	34 000
1/8	48 000
1/16	63 000

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The pressure is roughly 0.01 atmosphere at 100 000 feet and it is 10^{-11} atmosphere at 300 miles. The rule lacks precision because of the temperature variations in the atmosphere. From 0 to 35 000 feet, the temperature of the atmosphere decreases approximately 3.5° F for each 1000 feet. From 35 000 to 100 000 feet, the temperature is nearly constant at -67° F.

The atmosphere is a mixture of oxygen, nitrogen, carbon dioxide, water vapor, etc. Each of these gases has a different weight, so one might expect the heavier gases to sink toward sea level and the lighter gases to float toward the heavens. Actually, the turbulence of the weather band around the Earth produces so much mixing that the atmospheric composition does not change much up to an altitude of about 100 miles. There is a distinct helium band (fig. 1-4) at 600 miles that blends into a hydrogen layer at higher altitudes. Atomic oxygen and ozone can be formed below 600 miles, and ionization is probable. The variation in atmospheric composition with altitude implies that the absorption of the radiated energy of the solar spectrum will also vary with altitude. Furthermore, when that energy is absorbed, chemical compounds are formed that intensify or modify the absorption characteristics of the atmosphere. The resulting composition, in combination with the Earth's magnetic field and the solar intensities, leads to our weather, to our radio transmission, and to other phenomena such as northern lights, magnetic storms, etc.

Visible radiation and radio waves penetrate the atmosphere to add heat to the Earth's surface. All other forms of radiation are generally absorbed before they reach the surface. The upper atmosphere can reach very high temperature levels, but, of course, the density is low.

Infrared radiation can be transmitted when the skies are clear, but it is absorbed by cloud cover. This is why on a clear night, even though the air temperature is above
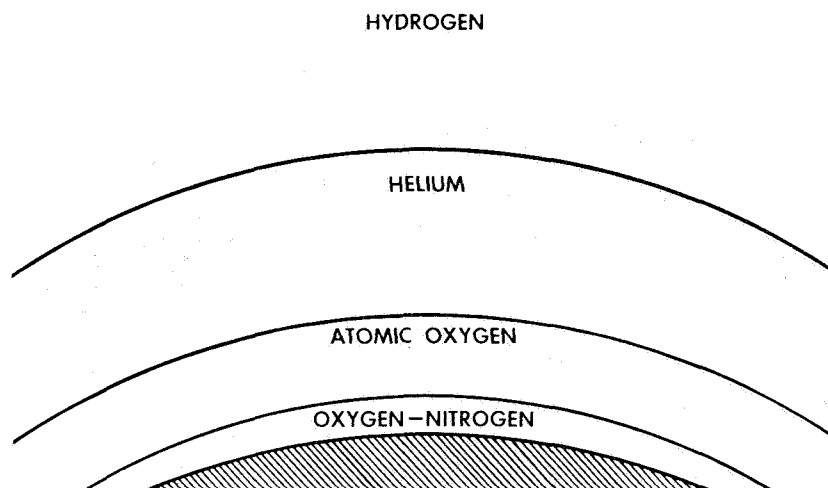
HYDROGEN

HELIUM

ATOMIC OXYGEN

OXYGEN—NITROGEN

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Figure 1-4. - Atmospheric composition.

freezing, frost can result if sufficient infrared heat of the Earth's vegetation is radiated into space to lower the planet surface temperature below the freezing point.

The atmosphere is opaque to ultraviolet rays with wavelengths below 2900 angstrom units. These rays cause the ionization in the ionosphere and generate the ozone layer at an altitude of about 15 miles, but they do not penetrate the ozone layer. The absorption of the ultraviolet rays explains the rise in temperature of the chemosphere, the air layer that overlaps and lies above the stratosphere. At higher altitudes, ionization, X-ray absorption, cosmic-ray absorption, and other complicated processes probably influence the heat and mass transfer and radio-wave reflection characteristics of our atmosphere.

Radio transmission depends on several different kinds of waves (fig. 1-5). The ground wave is that part of the total radiation that is directly affected by the presence of the Earth and its surface features. The two components of the ground wave are the Earth guided wave and the space wave. The tropospheric waves are those that are refracted and reflected by the troposphere. This refraction is due to changes in the index of refraction between the boundaries of air masses of differing temperature and moisture content. The ionospheric wave is that part of the total electromagnetic radiation that is directed through or reflected and refracted by the ionosphere. For nearby communication, the ground waves serve. For larger distances, refraction of the sky waves through the ionosphere is required. As shown in figure 1-5, a greater amount of bending is required to receive the signal at R_1 than at R_2. A skip zone of no received signal occurs between the limit on the ground-wave propagation distance and the bending limit position of the sky-wave receiver.

The refractive index is close to 1 in the troposphere so that refraction is generally slight. With an increase of altitude, layers of ionization are formed by the action of
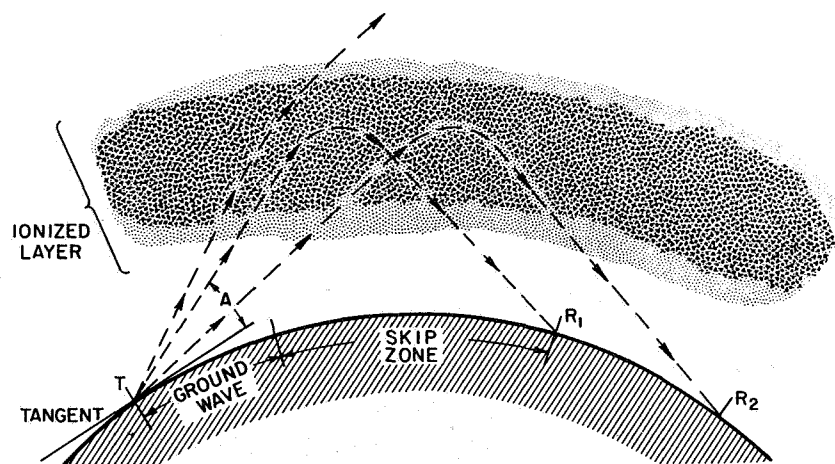

Figure 1-5. - Refraction of sky wave.

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ultraviolet light on oxygen, nitrogen oxide, etc. Free electrons are therefore available to change the dielectric constant and the conductivity of the region for the relatively low frequencies of radio transmission. Much greater refraction of radio waves occurs in the ionosphere than in the troposphere.

Layers of ionization have been observed by reflection of radio waves, and they are designated as the D, E, F1, and F2 layers. The D ionization layer, at altitudes of 40 to 50 miles, only persists in the daytime, and the intensity of ionization is proportional to the height of the Sun. In this layer the density of ions and electrons is so high that recombination quickly occurs in the absence of the Sun's radiation. The E layer is largely due to ionized oxygen atoms at altitudes of 60 to 80 miles. The intensity of ionization is greatest at local noon and is almost zero at night. The F layers have their maximum ionization at an altitude of about 175 miles. Here the density of ions is so low that recombination with electrons takes place only slowly. The minimum ionization intensity occurs just before sunrise. In the daytime, there are two F layers.

In the ionosphere, the degree of ionization depends on the intensity of the solar radiations. Therefore, ionization varies from nighttime to daytime, from summer to winter, with the 28-day period of the Sun's rotation, and with the 11-year sunspot cycle. Ionization is greatest during the period of maximum sunspot activity. The ionosphere is also strongly influenced by magnetic storms that may last several days. These so-called storms include unusual disturbances in the Earth's magnetic field along with accompanying disturbances in the ionosphere.

For a given ion density, the degree of refraction becomes less as the wavelength becomes shorter. Bending of the waves is less at high frequency than at low frequency because of the inertia of the ionization electrons. At the very high frequencies corresponding to TV channels, this bending is so slight that the wave does not return to Earth. This condition leads to the so-called "line of sight" limitation on radio waves.

It is evident that the conditions in the ionosphere are subject to the whims of the solar weather. By monitoring the conditions of the ionosphere with radio wave reflections, the long-distance communication networks can choose frequencies for best reception by use of extensive correlations. The Bureau of Standards also publishes prediction charts 3 months in advance on the usable frequencies above 3.5 megacycles for long-distance communications.

The use of satellites and high frequencies would allow long-distance radio-communication systems to be free from the vagaries of the Sun. Because the wave would be transmitted through the atmosphere, the system would be dependable irrespective of solar disturbances, seasons, time of year, sunspot cycles, etc. The Telstar, Relay, and Early Bird satellites are dramatic experiments demonstrating the feasibility of such communication systems.

Various types of satellites can be used as links in a communication system. One
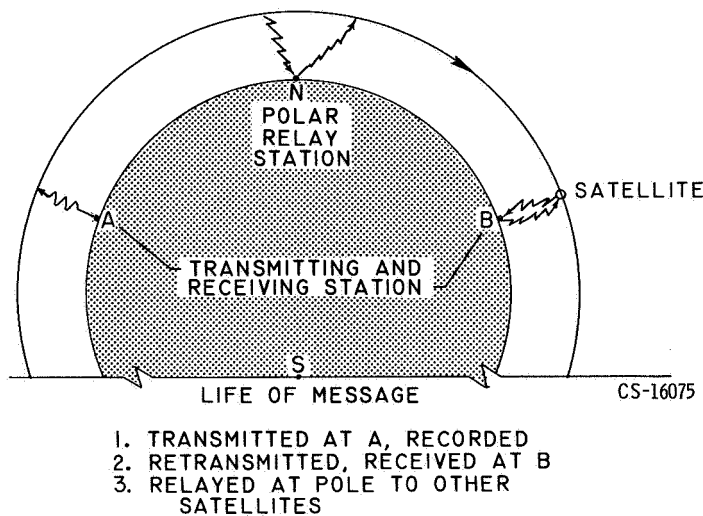
Figure 1-6. – Operation of message relay satellite.

type is the message relay satellite shown in figure 1-6. In this system the satellite contains a tape recorder, and messages transmitted from ground station A, when the satellite is over that point, are recorded and stored by the satellite. Later, when the satellite passes over ground station B to which the messages are addressed, that station triggers the relay with a command signal, and the satellite transmits the messages which it has stored. While ground station B is receiving messages from the satellite, the station may also be transmitting, on a different frequency, other messages to be carried by the satellite to other ground stations. Also, messages may be relayed from one satellite to another by means of a polar relay station.

The first example of a message relay satellite, and the world's first communications satellite, was Project Score, which was launched by the United States on December 18, 1958. This satellite was used to deliver President Eisenhower's Christmas message to the world on December 24, 1958. Message relay satellites might be used to relay military dispatches or as links in a rapid mail system.

Passive satellites can serve in a communication network if there are enough of them. In this system, the signal transmitted from a ground station to a satellite is reflected down to other ground stations. Satellites of this type include the Echo balloon configurations, the wire dipoles of Project Westford, and proposed balloons shaped to improve the signal reflection strength. Passive satellites generally must be at fairly low altitudes in order to give sufficient signal strength at the receiver. This problem arises because the strength of the signal transmitted to the satellite, even with a very good antenna, essentially diminishes as the inverse square of the distance, and the strength of the reflected signal returning to Earth diminishes at the same rate. Thus, the signal strength at the receiving station is proportional to the inverse fourth power

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of the altitude. Hence, altitudes of several thousand miles are about the upper limit. Since individual satellites at these low altitudes do not remain in best signal-reflecting position for very long, many satellites would have to be employed to maintain continuous communication between any two stations.

Active satellites, such as Telstar and Relay, receive and amplify the signal before transmitting it back to a ground station. Therefore, these satellites can be used at much higher altitudes than the passive satellites. A satellite which is placed into an equatorial west-to-east orbit at an altitude of 22 300 miles is said to be in a stationary orbit; that is, its orbital period coincides with that of the Earth's rotation, and the satellite remains nearly stationary in the sky relative to the Earth. This type of satellite is known as a synchronous satellite. Syncom, shown in figure 1-7, is the first synchronous active repeater communications satellite. A single synchronous satellite can provide communication for nearly a hemisphere; three such satellites can cover the entire Earth, except for a small region around the poles. Syncom currently provides our most reliable system of communication with our forces in Viet Nam.

The faint, general illumination of the sky visible from the ground on a clear, moonless night is known as airglow. This light source originates at an altitude of approximately 90 to 100 kilometers and is caused initially by a triple collision of oxygen atoms. In the high vacuum of space, one of these oxygen atoms retains electrons in an elevated energy level; that is, the atom assumes a metastable state. Some time later, this forbidden neutral oxygen atom releases its energy at a wavelength of 5577 angstroms
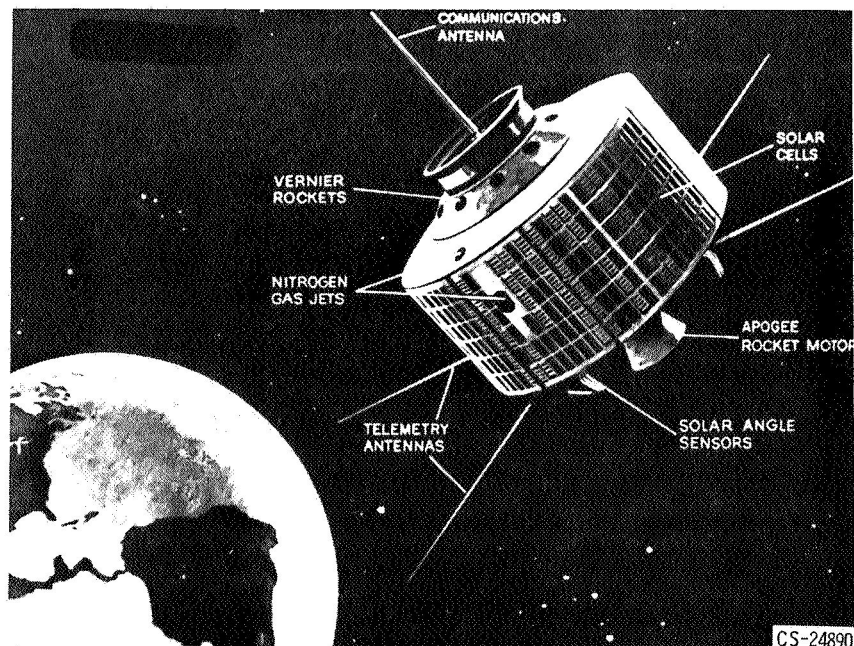

Figure 1-7. - Syncom satellite.

to produce the airglow. Conclusive proof of the cause of airglow was provided by astronaut M. Scott Carpenter, who, during his orbital flight on May 24, 1962, observed the airglow through a special filter which passed light only at a wavelength of 5577 ±10 angstroms.

This airglow is by far the best horizon for the astronauts. Because stars can be seen between the airglow and the Earth, astronaut Carpenter was able to determine the altitude of this airglow horizon quite accurately by noting the exact time when individual known stars entered and left the airglow region. Since the altitude and position of the Mercury capsule were known, the rest of the computation followed in a straightforward manner.

What can the astronaut see from a satellite? He certainly can see the heavens un-hampered by the turbulence of the atmosphere; stars, therefore, do not twinkle. He can get a marvelous view of the Earth's cloud cover and weather patterns; perhaps he can even detect hurricanes in their formation (fig. 1-8) before ground-based stations can do so. (Fig. 1-8 is not the best cloud-cover picture that has been obtained, but it is the first photograph of a hurricane in the making taken from a rocket.) The Tiros satel-lites, which have provided much better pictures than figure 8, have demonstrated their ability to aid in the observation and mapping of worldwide weather patterns. These satellites were used to locate accurately the center of a tropical storm after conventional tracking methods had provided a 500-kilometer error in its location. The break in an Australian heat wave was predicted accurately from data provided by Tiros II, and hurricane Esther was discovered by Tiros III. These contributions will be followed by others from more sophisticated satellites such as Nimbus and, still later, Aeros.

Gross weather patterns are definitely visible to an astronaut, but his ability to de-tect details and Earth surface characteristics has certain limitations. The quality of
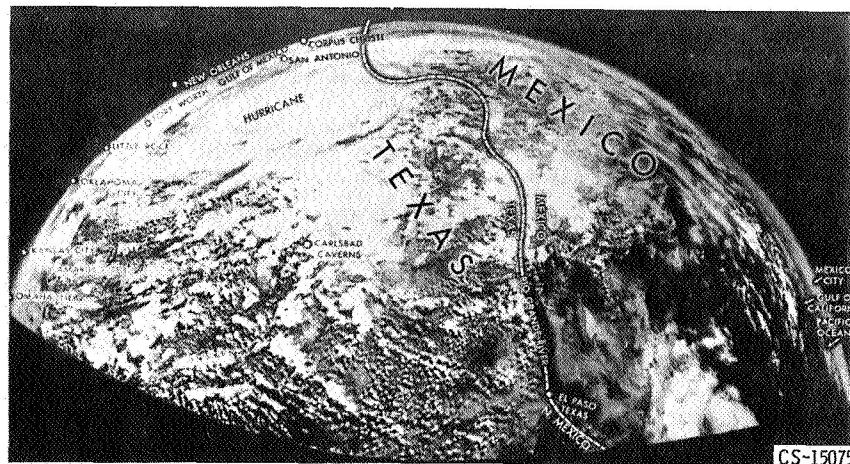

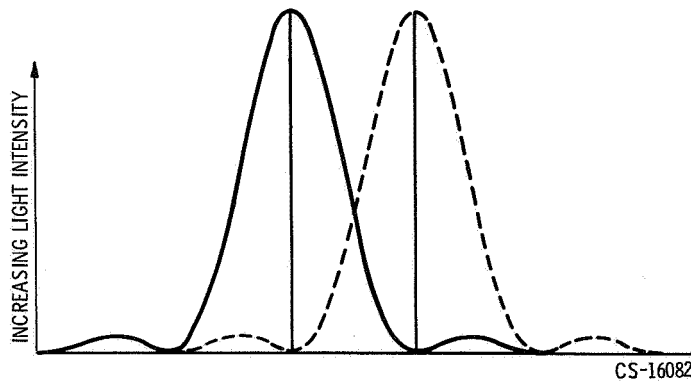Figure 1-8. - Rocket view from 100-mile altitude.

Figure 1-9. - Diffraction pattern of two point light sources (circular aperture).

the image from an optical or radar viewing system is limited by the fact that electro-magnetic radiations have wavelike characteristics. A circular aperture on such a viewing system will generate a diffraction pattern so that a point source will not give a point image on the viewing screen. The individual light intensities from the images of two point sources are plotted in figure 1-9.

Clearly, if two images are closely spaced, the light patterns will blend so that they cannot be distinguished as separate. Conventionally, this closest spacing for resolution occurs when the central maximum intensity of the diffraction pattern of one point source falls at the first minimum intensity of the second point source. This gives a minimum angular resolution of

$$\varphi = 1.22 \frac{\lambda}{a} \tag{2}$$

where φ is the angular separation of the two point sources in radians, λ is the wave-length of the radiation, and a is the aperture diameter. As shown in the sketch below, this angle φ is also equal to the distance x between the two point sources divided by the distance d of the two sources from the observation station. Hence,

$$\varphi = 1.22 \frac{\lambda}{a} = \frac{x}{d} \tag{3}$$

and the quantity x approximates the uncertainty of position or definition of a viewed object.

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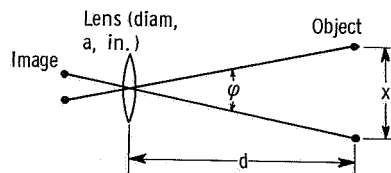
By using equation (3), a 1-inch-diameter optical telescope mounted on a satellite 200 miles above the Earth can be used to resolve point light sources if they are more than 23 feet apart. With a 12-inch scope, the resolved distance is 1.9 feet. This resolved distance approximately represents the fuzziness of the boundaries of the object under observation. Thus, with a 12-inch scope, ships, roads, buildings, trains, and general map characteristics, including automobiles in parking lots, could be determined. A satellite equipped with a reasonable telescope (12-in. objective lens) probably could be used to detect, classify, and establish the locations of surface ships, military installations, and troop movements of an alien power without the aid of spies or decoding experts.

The question might be raised as to whether there is sufficient illumination for observing the Earth's surface from a satellite. During daytime, there is certainly ample illumination. The light-transmission coefficient through the entire atmosphere is approximately 85 percent at the zenith. Therefore, from a satellite, the Earth appears to be about six or seven times as bright as the full Moon. The brightness of an object viewed from the zenith through the entire atmosphere is about equivalent to that of an object 5.3 miles away along the surface of the Earth.

Useful observations of the Earth can be made with a manned satellite even at night. According to Russell (ref. 1), the detection of a point light source by the unaided human eye requires a radiant flux, from the light source, of at least 2.5×10^{-9} erg per second. (Radiant flux is the rate of flow of radiant energy.) A 1-watt light bulb with a 1-percent efficiency should, therefore, be observable from a satellite located at an altitude of 200 miles and equipped with a 12-inch-objective telescope. A photographic plate with an exposure time of 1 minute could probably detect a 60-watt light bulb.

It is a well known fact that the stars appear to twinkle while the planets do not. This twinkling effect is due to atmospheric turbulence and temperature gradients. These disturbances modify the index of refraction of the atmosphere and cause local bending of the light rays passing through it. Thus, the observed position of a star changes transiently with time, and this change causes the twinkling appearance. The position of a star as seen through the atmosphere is statistically uncertain by 1 to a few seconds of arc. Because the angular size of the planets is larger, the twinkling is not apparent, even though it is still present. Mars, for example, subtends an angle from Earth of about 17 seconds at closest approach. A pinpointed object on the rim of the Mars disk, or on the Moon for that matter, would have the same circle of confusion due to turbulence as does a star. The positional uncertainty of a satellite as viewed from the ground might be as much as 3 seconds of arc associated with atmospheric turbulence. The corresponding distance error Δx_s for a satellite at 200 miles, as seen from the ground, is about 15 feet.

The ability to locate an object on the ground from a satellite is much more precise
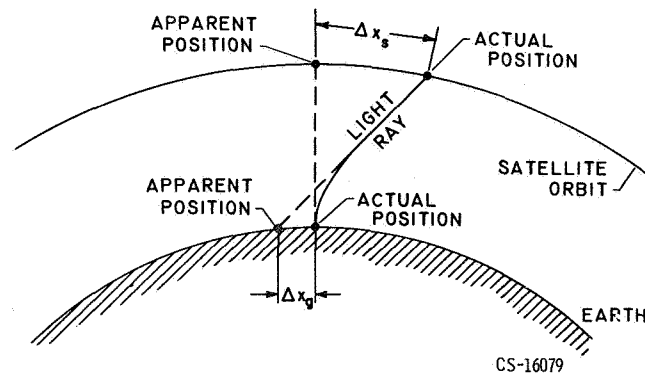
Figure 1-10. – Atmospheric shimmer.

than the ability to locate a satellite from the ground. This is shown in figure 1-10 by the relative sizes of the positional errors Δx_g and Δx_s. The index of refraction of a gas is related to its density, and the density of the atmosphere decreases exponentially with altitude. Hence, the air layers near the surface of the Earth (where the density of the air is high) produce the greatest bends on the light path. In figure 1-10, the same light path is traveling between the ground observer and the satellite astronaut, but each appears to see his object along the projected tangent to the local light path. The bending is great near the ground observer while hardly any bending occurs near the satellite. In fact, the ratio of the errors $(\Delta x_s/\Delta x_g)$ can be shown to be about 45 to 1 for a 200-mile-altitude satellite. Thus, atmospheric shimmer causes an error Δx_g of only a few inches in the astronaut's observation of the ground. An objective lens with a diameter of up to 6 feet could be used for viewing the ground from a satellite at an altitude of 200 miles before the inherent optical resolution would be better than the resolution due to turbulence and atmospheric shimmer.

Since the orbital path of a satellite has considerable bearing on the ability of an astronaut to observe the ground, a brief discussion of orbits (fig. 1-11) might be of
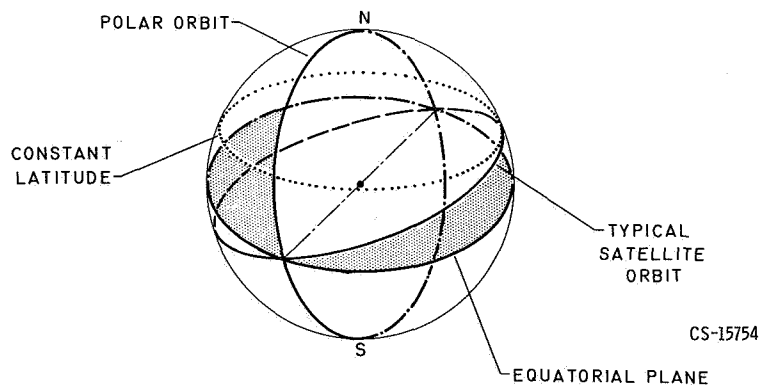

Figure 1-11. – Satellite orbits.

interest. If the satellite is launched from either pole, only a polar orbit can be established. In this case, the entire Earth comes under surveillance as it rotates under the satellite's orbit. Clearly, however, it is not possible to establish an equatorial orbit with a ballistic launch from the poles. In fact, the inclination of the orbital plane to the equator must be equal to or greater than the latitude of the launching site. Thus, only from the equator can all kinds of orbits, that is, equatorial, polar, etc., be established, unless midcourse thrusting is employed.

The position of the orbital plane of the satellite depends on the inhomogeneities of the Earth's gravitational field. The Earth is not a perfect sphere, so that the idealized variation of the gravitational attraction with the inverse square law is only approximately true. The actual Earth bulges at the equator; that is, it somewhat resembles a sphere with a belt around the equator. The gravitational pull of this belt is stronger on a satellite at the equator than at the poles. The Earth's bulge, therefore, influences the orbit of a satellite. The perturbations of this orbit may, in turn, be used to make geophysical measurements of the Earth's gravity. Such studies with the Vanguard I satellite led to the discovery of the pear-shaped Earth.

There are two important ways in which the equatorial bulge influences the orbit of a satellite (fig. 1-12). First, the bulge deflects the satellite toward the normal (perpendicular) to the equator each time the satellite crosses the equator. Thus, the plane of an eastwardly launched satellite rotates toward the west. The approximate rate of rotation, in degrees per day, is given by the equation

$$R = 8 \cos \alpha \tag{4}$$

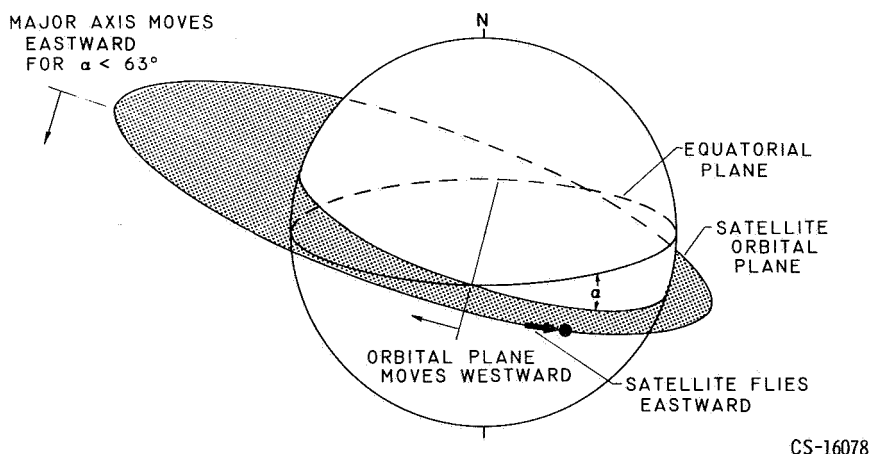where α is the inclination, in degrees, of the orbital plane to the equatorial plane.

Figure 1-12. - Effect of Earth's equatorial bulge on satellite orbit. (Bulge not shown in this figure.)

Second, the bulge causes the satellite to speed up when it crosses the equator. This speedup, in turn, causes the major axis of the elliptical path to rotate in the plane of the orbit. The approximate rate of rotation, in degrees per day, is given by the equation

$$S = 4(5 \cos^2 \alpha - 1) \tag{5}$$

The direction of this rotation reverses above latitudes of approximately 63°. The plane angle, or inclination, of the early Russian satellites was approximately 63°. Thus, the perigee of the orbit remained over Russia, and data transmission was improved. The numbers in equations (4) and (5) are for a 200-mile-altitude satellite.

A satellite in orbit is always falling toward the Earth. Because of the Earth's curvature, however, the horizon keeps dropping so that the satellite never reaches the surface but continues to go around the Earth. A body in free fall, such as a satellite, experiences the phenomena associated with weightlessness.

The weightless environment is still of considerable worry to space scientists. The influence of weightlessness on man for extended periods of time might lead to deteriorations of muscular and bodily functions through lack of stimulation. The fuel in a rocket tank may settle at the top, the bottom, or the sides of the tank. Hence, venting of the tank may be as much of a problem as locating the fuel at the tank discharge port. A detailed discussion of weightlessness is presented in chapter 8.

The thermal environment in space depends greatly on location. Space has such a high vacuum (of the order of 10^{-16} millimeter of mercury or better) that only a few molecules of hydrogen are present in each cubic centimeter. Hence, the normal definition of temperature that depends on a statistical distribution of molecular or vibrational speeds probably has no meaning. Also, the heat transfer to or away from a spacecraft must be principally by radiation. Therefore, the temperature of space might be defined as that equilibrium temperature that a body would assume in absence of sunlight or planet light. This temperature for deep space is perhaps 3° to 4° K but may be as high as 20° K in portions of the Milky Way. The temperature of a body in solar space is determined by equating the energy absorption by the body from the solar and planet radiations to the energy reradiated to deep space and to any nearby objects. The radiation from a black body is proportional to the fourth power of the absolute temperature of the black body and of the environment surrounding it. This relation is shown by the equation

$$E = \sigma(T_1^4 - T_2^4) \tag{6}$$

where E is the radiant emittance of the black body, σ is the Stefan-Boltzmann constant

of proportionality, T_1 is the absolute temperature of the black body, and T_2 is the absolute temperature of the environment surrounding the black body.

The energy received near the Earth from the Sun is 1.34 kilowatts per square meter. This energy is largely in the visible range. If this energy is absorbed by a spacecraft, the reradiation is largely in the infrared range. Since materials have different absorption and emissivity coefficients according to the wavelength of the radiation, the temperature of spacecraft may be controlled by selection of appropriate surface coatings. A coating with high absorptivity in the visible region and low emissivity in the infrared region has a higher equilibrium temperature than if the reverse is true. By combinations of stripes and selected coatings, spacecraft temperatures are usually adjusted to be near normal room temperatures. The coatings are quite sophisticated since they are tailored for particular orbital paths or missions. Mariner, for example, requires a different coating than do satellites near Earth. Even on near-Earth satellites, the coatings are altered if the orbital path is changed because of delays of a few days at launch.

A simple energy balance will indicate the variations of equilibrium temperature on a spacecraft in solar space. If we assume a sphere with sufficient conductivity to have uniform surface temperature, the black body solar energy absorbed will vary inversely as the square of the distance from the Sun. The energy radiated will be proportional to the fourth power of the surface temperature. Thus, the equilibrium temperature obtained by equating the absorbed and radiated energy varies inversely as the square root of the radial distance from the Sun.

The Earth has a magnetic field which has an important influence on the near-Earth space environment. A charged particle moving through space acts like an electric current. An electric current in a magnetic field generates a force perpendicular to the direction of the current and of the magnetic field, as shown in the following sketch:
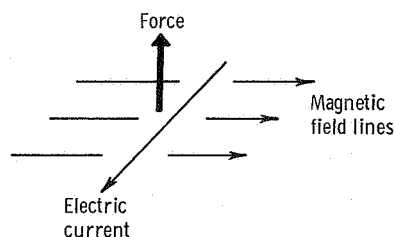
A charged particle moving parallel to the magnetic field is not affected by the field. However, a charged particle moving perpendicular to the field experiences a force which causes it to move around a field line in a circular path. If a charged particle approaches the magnetic field at some angle other than 90°, the particle will spiral along a field line as shown in the following sketch:

Charged
particle path

Magnetic
field line
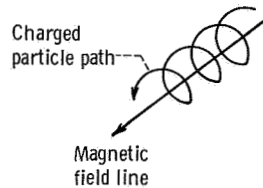
Any force on the charged particle in a constant direction normal to the magnetic field will cause the charged particle to travel alternately slower and faster while it is spiraling around the field line. Hence, the path radius of curvature will alternately increase and decrease. This will cause the particle to drift sideways in a direction perpendicular to the force and the field lines as shown in figure 1-13. Note that both positive and negative charges drift in the same direction.

ION

DRIFT DIRECTION

ELECTRON

PERPENDICULAR
MAGNETIC FIELD

ELECTRIC FIELD

CS-18299

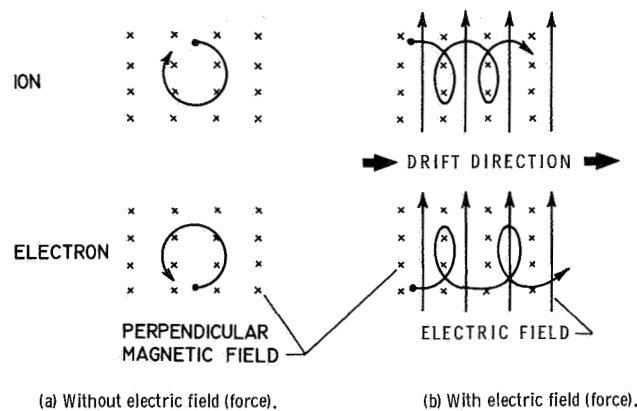(a) Without electric field (force).   (b) With electric field (force).

Figure 1-13. - Charged-particle motions in magnetic and electric fields.

If the field is increasing in the direction of the spiral motion, then the radius of the path will decrease, and the converging field lines will produce a force to reflect the particle back in the direction from which it came (see following sketch). Thus, we could make magnetic mirrors to trap charged particles in the region between increasing magnetic fields.

Path of
charged particle

Field lines

Increasing magnetic
intensity

Distance

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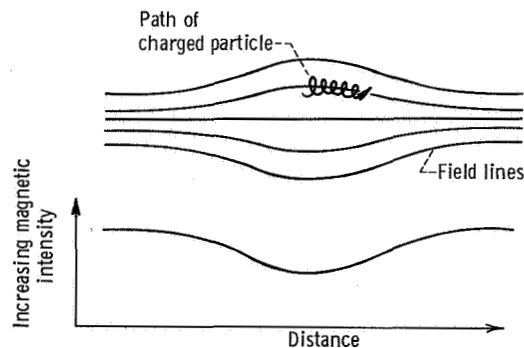
Figure 1-14. - Explorer XII satellite.

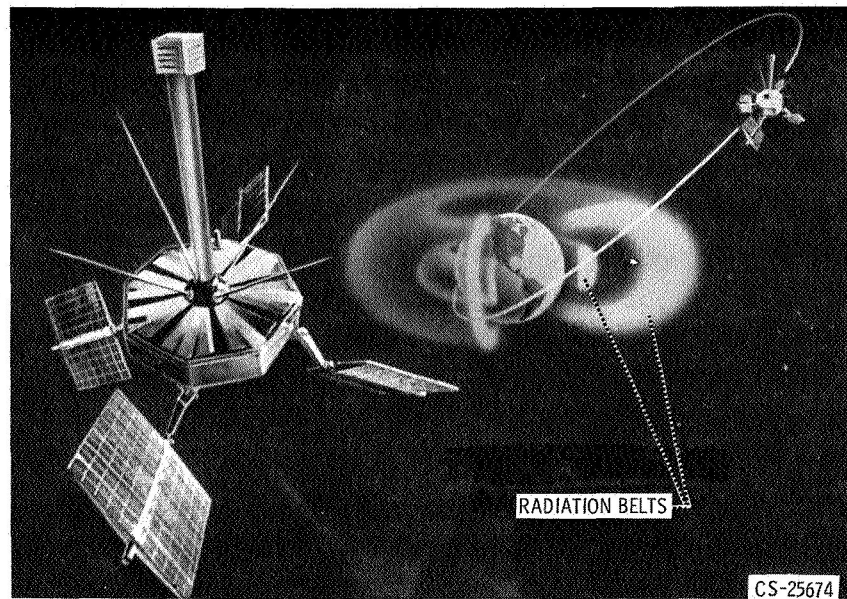The Earth has a magnetic field surrounding it, and this field increases toward the poles. Hence, the Earth's magnetism forms a magnetic bottle to trap charged particles. These particles are spiraling around the magnetic field lines, bouncing back and forth along spiral paths from pole to magnetic pole. Simultaneously, there is a very small drift velocity in the circumferential direction associated with the gravitational field. Thus, the charged particles diffuse around the Earth to form the Van Allen belts. (A detailed discussion of the Van Allen belts is presented in ref. 2.) The Van Allen belts generally do not persist to the lower altitudes of Project Mercury space flights; if they did, the upper atmosphere would soon cause their decay. The belts are strongest in the regions between 1 and 10 Earth radii. Data from Explorer XII (fig. 1-14) reversed previous concepts of the belts; the entire region is actually a single system of charged particles instead of two distinct belts. These charged particles are trapped by the Earth's magnetic field.

The chief constituents of the Van Allen belts are electrons and slow-moving protons, and the quantities of each vary with altitude. At 2000 miles, the predominant particles are protons with energies of tens of millions of electron volts (10 MeV). This region has been modified by nuclear explosions. At 8000 miles, protons with only a fraction of an MeV predominate, and at 12 000 miles, protons with energies of 0.1 to 4 MeV and electrons with energies up to 2 MeV are blended. The exact source of the charged particles in these regions is still a matter of controversy. The formation of one new artificial belt, however, is well understood. In this one, a high-altitude nuclear explosion filled the region with electrons. The surprise associated with this one is that

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the strength of the belt persisted much longer than originally estimated. It has knocked out the power supplies of several satellites. This degradation is due to damage to the solar cells.

The outer regions of the Van Allen belts contain large numbers of low-energy protons. These protons pose less of a radiation hazard than the high-energy electrons. The occupants of a space vehicle passing quickly through these regions on the way to the Moon or beyond would be in little danger from the protons but would need to be protected from the X-rays generated by impingement of electrons on the spacecraft components. On the other hand, the protons would pose a serious problem to the occupants of even a heavily shielded, electric-propulsion spacecraft or an orbiting laboratory if the residence time were 2 weeks or longer.

The most common unit for a radiation dose is the rem (roentgen equivalent man). The rem is that quantity of any type of ionizing radiation that, when absorbed in the human body, produces an effect equivalent to the absorption of 1 roentgen of X or gamma radiation at a given energy. The roentgen is the quantity of X or gamma radiation required to produce (in 1 cubic centimeter of dry air) ions carrying 1 electrostatic unit of positive or negative charge. Since man has a radiation exposure limit of 25 rem, a 2-week exposure time in the inner Van Allen belt would require a shield weight of approximately 140 grams per square centimeter (55 in. of water thickness). The normal background cosmic-ray intensity from all sources is about 0.65 rem per week. Thus, with a 25-rem exposure limit, an unshielded space traveler would reach his limit on radiation exposure from this source alone in about 38 weeks.

It should be pointed out that the Van Allen belts are not steady and unchanging. The belts have been modified by nuclear explosions, and they are also modified and distorted by the solar winds. During solar flares and intense sunspot activity, tongues of plasma (fig. 1-15) along with a trapped magnetic field are shot out toward the Earth. The geo-
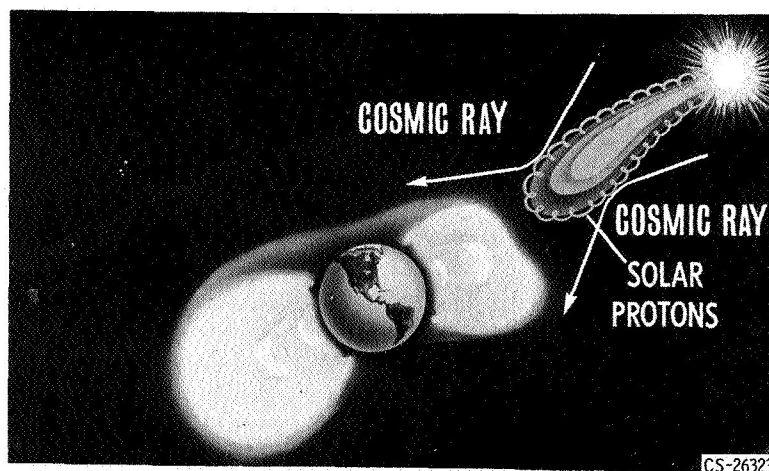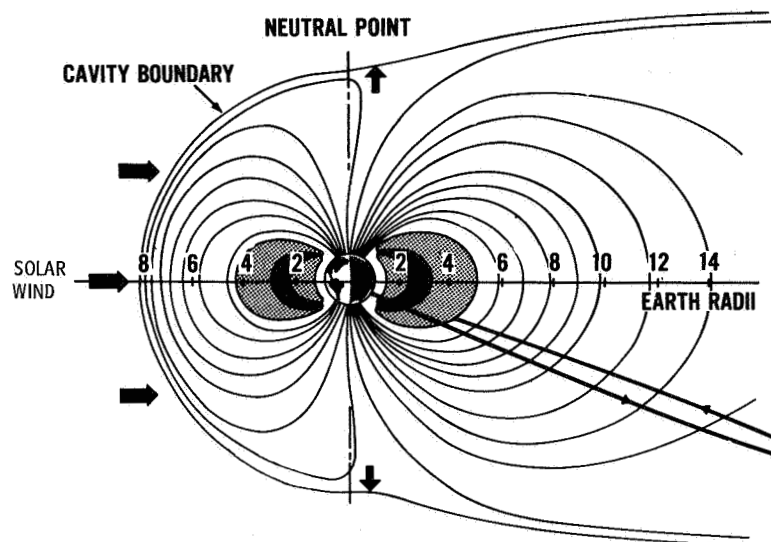

Figure 1-15. - Radiation belts and solar disturbance.

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Figure 1-16. – Distortion of radiation belts by solar wind. Solar wind has flux of 10 protons per centimeter and velocity of 500 kilometers per second.

magnetic sphere of the Earth forms a shock wave in this plasma sheath; consequent distortions of the Van Allen belts occur as shown in figure 1-16. The edge of the geomagnetic sphere confined inside this shock wave and on the side of the Earth facing the Sun is at an altitude of some 30 000 to 40 000 miles.

Solar flares pose a serious threat of radiation to man. These flares eject high-energy particles, most of which are protons with energies ranging from less than 10 MeV to almost 50 BeV. The classification of solar flares is shown in table 1-I. The minor flares of classes I-, I, and II are not particularly troublesome, but the major flares of classes III and III+ are relatively serious. Sixty such major flares were recorded between 1956 and 1961; therefore, the average rate of occurrence is approximately once a month. Occasionally, giant solar flares larger than those of class III+ occur. Seven of these giant flares have been observed during the past 18 years.

Weight limitations may restrict the radiation shield of the Apollo spacecraft to be-

TABLE 1-I. - SOLAR-FLARE DATA

Class	Fraction of visible hemisphere	Duration, min	Energy	Frequency of occurrence
I-	25×10^{-6}	5 to 20	--------	2/hr
I	100×10^{-6} to 250×10^{-6}	4 to 43	--------	
II	250×10^{-6} to 600×10^{-6}	10 to 90	--------	
III	600×10^{-6} to 1200×10^{-6}	20 to 155	100 MeV	12/yr
III+	$>1200 \times 10^{-6}$	50 to 430	1 to 40 BeV	

tween 10 and 30 grams per square centimeter. Such a relatively thin shield would protect man for the short times he might spend in the Van Allen belts, and it would offer partial protection against minor and major solar flares. Thus, the greatest source of danger would be the unpredicted giant solar flares.

Almost all protons of energies greater than 100 to 200 MeV will pass through a 10- to 30-gram-per-square-centimeter shield. A class III+ solar flare has flux levels as high as 10^4 protons per square centimeter per second, and large numbers of these protons have energies greater than 100 to 200 MeV.

The energy loss mechanism (ionization and scattering) in thin shields is orderly and well understood. In thin shields, the protons collide only occasionally with a shield nucleus, and hence secondary radiations are unimportant. Future space flights of very long duration, however, will require thick shields. Then the secondary radiations arising from nuclear reactions in the radiation shield and spacecraft material will become important. In cascade reactions, a proton enters a heavy nucleus, which then disintegrates to a lighter nucleus and emits protons and neutrons. These, in turn, cause other disintegrations. In evaporation reactions, a proton enters a nucleus to form a radioactive atom. Such an atom might decay and emit a neutron, which could cause further reactions. As the shield thickness increases, the secondary radiations become increasingly more important relative to the primary ones.

The danger from giant solar flares results partly from the inability of Earth scientists to predict them. Some success has been obtained by first calculating the size of the shaded area (penumbra) surrounding each sunspot group (fig. 1-3, p. 3). (The size of the penumbra might be a measure of sunspot intensity.) The numbers obtained from these calculations are then used to predict the expected relative safety of a 4- to 7-day space flight as proposed for the Apollo program. Malitson (ref. 3) examined the results of such calculations and drew the following conclusions:

(1) If the established criterion for unsafe flight due to a sunspot group is a penumbral area larger than 1000 millionths of the solar surface, the usable flight time is reduced by 33 to 40 percent, and encounters with approximately half the number of giant solar flares are still possible. From the standpoint of safety, this criterion is obviously unsatisfactory.

(2) If a reduced penumbral area of 500 millionths of the solar surface is used as the criterion for unsafe flight, then the safe flight time is reduced to 20 to 35 percent of the actual usable flight time. This criterion would have allowed only one encounter with a giant solar flare during each of the years 1949 and 1950.

(3) During the year 1951, even if the criterion for unsafe flight had been a penumbral area larger than 300 millionths of the solar surface, two encounters with giant solar flares could have occurred.

These calculations clearly indicate that the present methods of predicting giant
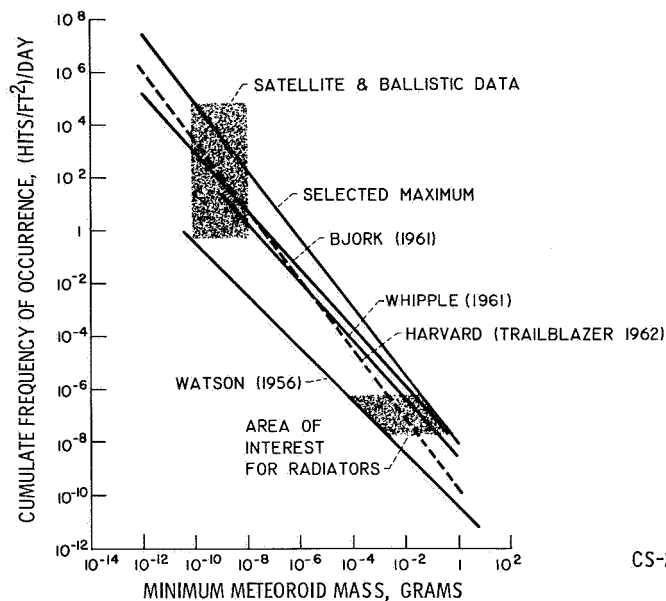
Figure 1-17. - Meteoroid mass-frequency distribution.

solar flares are inadequate. Therefore, these flares would be dangerous sources of radiation on extended-time manned missions to Mars and other planets.

Another source of danger to a spacecraft is the meteoroid. A meteoroid is any of the countless small bodies moving in the solar system. If the meteoroid passes with incandescence through the atmosphere, it is a meteor; if it reaches the surface of the Earth, then it becomes a meteorite. Meteoroids vary in both size and density. Some of them may be as light as snow, with a specific gravity of perhaps 0.15. The stony meteorites seen in museums have specific gravities of 2 to 3, while the specific gravities of the nickel-iron ones are about 7 or 8. The sizes of the meteoroids range from infinitesimal up to perhaps a few pounds or heavier. In Arizona there is a mile-wide crater which was formed by a meteorite. Obviously, a meteorite capable of producing such a change in the surface structure of the Earth must be very large.

Estimates of the mass-frequency distribution of meteoroids are shown in figure 1-17. The data for the curves are generally obtained by observers of meteor trails either visually or by means of radar. The curves in this figure show that particles which have a large mass have very low occurrence rates and, conversely, particles which have high occurrence rates have very little mass.

Figure 1-18 shows how the meteoroids are distributed in space. To an Earth observer, there are many more particles approaching the Earth from the leading hemisphere than from the trailing hemisphere as the Earth moves in orbit around the Sun. However, if these data are corrected for the speed of the Earth, then the results show that the majority of the particles are traveling in orbits around the Sun in the same
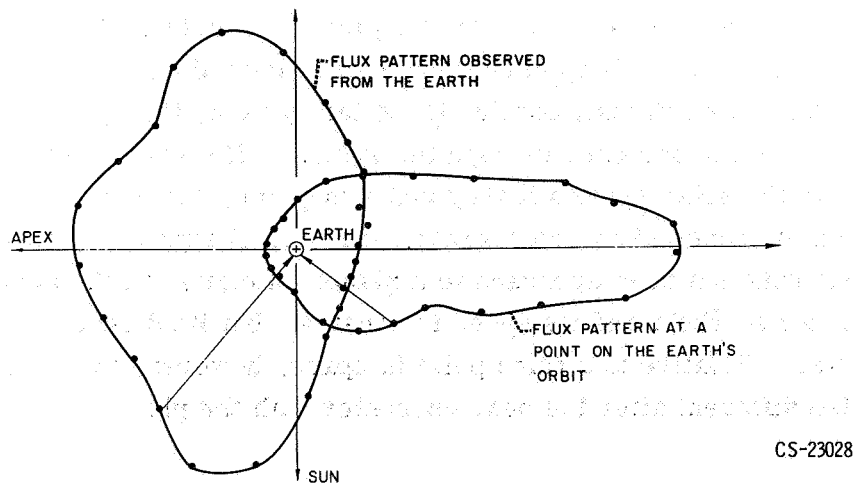
Figure 1-18. - Meteoroid flux distribution relative to Earth and to point on plane of ecliptic.
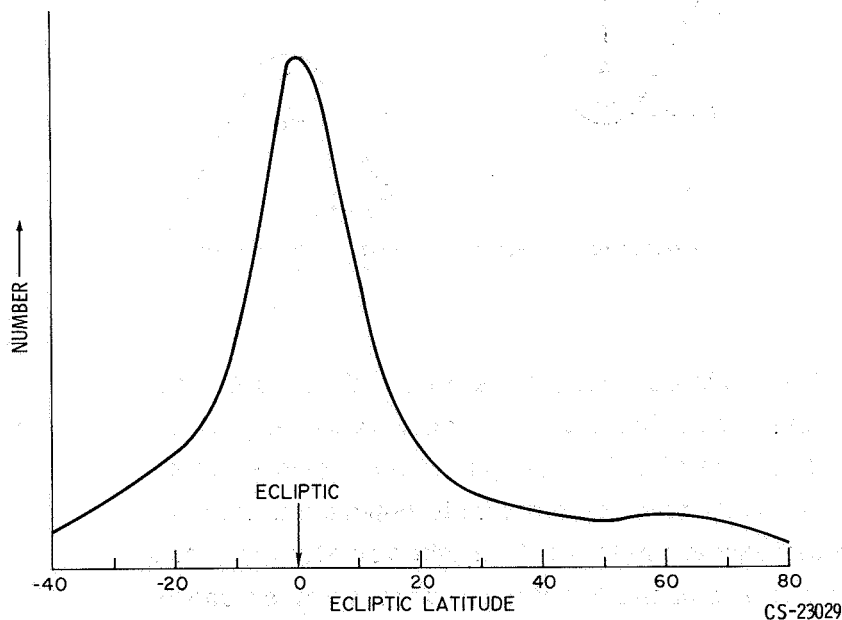

Figure 1-19. - Meteoroid distribution relative to plane of ecliptic.

general direction as the Earth.

The distribution of the meteoroids relative to the plane of the ecliptic (the orbital plane of the Earth about the Sun) is shown in figure 1-19. It is obvious that most of the particles are distributed within approximately 20° on each side of the plane of the ecliptic. The majority of the meteoroids are orbiting around the Sun, but some of them may also be trapped in orbits around our Earth-Moon system. The paths of some meteoroids form very large angles to the plane of the ecliptic, and these particles are probably of cometary origin. Scientists now assume that these meteoroids of cometary

origin have very low densities of less than 0.5 gram per cubic centimeter.

Scientific speculation has led to several theories regarding the origin of meteoric material. If meteoroids originate outside the solar system, they probably follow hyperbolic paths and make just one pass through the system. However, such meteoroids can become trapped in the solar system if they undergo gravity turns near one of the planets.

The following sketches show how a gravity turn can change the speed and direction of a meteoroid as it makes a near approach to a planet. Relative to the planet, the path of the meteoroid is a hyperbola and its speed is constant, but its direction is different after the near encounter. Relative to a fixed point in space, however, the speed of the meteoroid is also different after the near encounter with the planet.

Planet adds energy to meteoroid   Planet subtracts energy
                                          from meteoroid
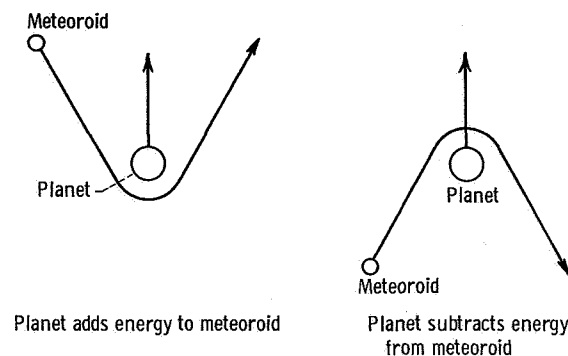
The meteoroids might come from the asteroid belt between Mars and Jupiter. Particles can diffuse out of this belt by a combination of gravity turns. The orbits of the individual particles can be altered upon close approach to another mass center. If this explains meteoroids, then the meteoroid population near Mars must be larger than near Earth. The meteoroids near Earth might actually come from the Moon. A meteoroid impact on the surface of the Moon may carry so much energy that four or five times as much mass as that of the impinging meteoroid might be knocked off the Moon's surface and propelled to an escape velocity. Some eminent scientists believe that the tektites (small glassy bodies of probably meteoric origin and of rounded but indefinite shapes) found on the Earth came from the Moon. Some people hold the theory that meteoroids originate in the tails of comets. This is an interesting theory, but it does not explain the origin of the comets themselves.

The principal reason for the great interest in meteoroids is that there is a finite probability that a space vehicle might be damaged or destroyed by meteoroid puncture. Therefore, the various components of a spacecraft must be made strong enough to prevent penetrations or destructive damage by meteoroids. Without sufficient and accurate meteoroid damage data, spacecraft would likely be underdesigned or overdesigned;

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underdesign could result in early loss of mission, while overdesign could result in overweight craft, sluggish performance, or compromised payload.

Manned exploration of the planets depends to a great extent on the planetary environments. This is why the interest in manned flights to Venus waned suddenly when data obtained from the Mariner II satellite indicated that Venus has a surface temperature of 800° F. Since more recent spectra showing the presence of water vapor on Venus have cast some doubt on the validity of the Mariner II data, some interest in the manned exploration of this planet is being revived. However, more instrumented-probe data are needed prior to any decision on the feasibility of manned landings on Venus.

Mars has also been considered as the object of manned exploration. However, a careful study of the environment on the Martian surface reveals that it is not at all attractive. For example, the atmospheric pressure at the surface is less than 10 millibars, which corresponds to the pressure at an altitude of approximately 100 000 feet above the Earth. The oxygen content is less than 1 percent, which is equivalent to the oxygen content at an altitude of approximately 160 000 feet above the Earth. The watervapor content on Mars is perhaps only 1/2000th of the moisture on Earth; therefore, rivers, lakes, and oceans are probably nonexistent. What little water there is on Mars may be salty. Also, the surface of Mars is probably bombarded with asteroids and meteoroids from the asteroidal belt. This condition may be much more serious than it is on Earth because of the greater meteoroid population near Mars and because of the thin atmosphere. On Earth, meteors penetrate to perhaps 50 000 feet altitude; a similar particle on Mars would strike the surface. Also, the theory of planet formation suggests that Mars has a solid core and no mountains of the folded type. With a solid core, there probably is no appreciable magnetic field, and hence, no trapped radiation belts of the Van Allen type. On the surface of Mars, severe radiation intensities can be expected during giant solar flares because of both the rarefied atmosphere and the lack of magnetic-field trapping of ionized particles. Thus, strong shielding would be required on the Martian surface during giant solar flares. To survive, man would have to take his Earth environment with him. Conditions are so hostile that colonization is probably out of the question in our times. Nevertheless, manned exploration of Mars will take place and can be justified solely on its scientific merits.

GLOSSARY

apogee. That point in the orbit of a satellite of the Earth that is farthest from the center of the Earth.

astronomical unit. The mean distance of the Earth from the Sun, amounting to approximately 93 million miles; used as the principal measure of distance within the solar system.

galaxy. A vast assemblage of stars, nebulae, star clusters, globular clusters, and interstellar matter, composing an island universe separated from other such assemblages by great distances.

ionization. The process by which neutral atoms or groups of atoms become electrically charged, either positively or negatively, by the loss or gain of electrons.

ionosphere. A layer of the Earth's atmosphere characterized by a high ion density. Its base is at an altitude of approximately 40 miles, and it extends to an indefinite height.

nebula. An immense body of highly rarefied gas or dust in the interstellar space of a galaxy. It is seen as a faint luminous patch among the stars.

perigee. That point in the orbit of a satellite of the Earth that is nearest to the center of the Earth.

refraction. The deflection from a straight path undergone by a light ray or a wave of energy in passing obliquely from one medium into another in which its velocity is different.

solar corona. The tenuous outermost part of the atmosphere of the Sun extending for millions of miles from its surface. It contains very highly ionized atoms of iron, nickel, and other gases that indicate a temperature of millions of degrees. It appears to the naked eye as a pearly gray halo around the Moon's black disk during a total eclipse of the Sun, but it is observable at other times with a coronagraph.

solar prominence. A tongue of glowing gas standing out from the Sun's disk, sometimes to a height of many thousands of miles, and displaying a great variety of form and motion. Prominences are especially numerous above sunspots.

sunspot. A disturbance of the solar surface which appears as a relatively dark center (umbra), surrouned by a less dark area (penumbra). Sunspots occur generally in groups, are relatively short lived, and are found mostly in regions between 30° North and 30° South latitudes. Their frequency shows a marked period of approximately 11 years. They have intense magnetic fields and are sometimes associated with magnetic storms on the Earth.

troposphere. That part of the Earth's atmosphere in which temperature generally decreases with altitude, clouds form, and there is considerable vertical wind motion. The troposphere extends from the Earth's surface to an altitude of approximately 12 miles.

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